A Robust Predictive Deadbeat Current Control for Five-Phase BLDC Drives under Healthy and Open-Circuit Faulty Conditions

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Abstract—Fault tolerant control of five-phase BLDC machines is gaining more importance in high-safety applications such as automotive industries and offshore wind generators. In many applications, traditional controllers (such as PI controllers) are used to control the stator currents under faulty conditions. These controllers have good performance with dc signals. However, in the case of missing one or two of the phases, appropriate reference currents of these machines have oscillatory dynamics both in phase- and synchronous-reference frames. Non-constant nature of these reference values requires the implication of fast current controllers. In this paper, model predictive deadbeat controllers are proposed to control the stator currents of five-phase BLDC machines under normal and faulty conditions. Open circuit fault is considered for both one and two stator phases, and the behaviour of proposed controlling method is evaluated. This evaluation is generally focused on first, sensitivity of proposed controlling method and second, its ability in following reference current values with fast speed. Proposed method is simulated and is verified experimentally on a five-phase BLDC drive.

***Index Terms*—** Fault tolerant control, deadbeat control, multiphase machines, permanent magnet motors,

I. Introduction

Due to their compactness and high efficiency, permanent magnet (PM) machines are becoming more popular in the field of variable speed drives. During the last years many studies have focused on torque improvement of these machines, which in fact is the control of stator currents in direct (i_d) and quadrature (i_q) directions [1].

Comparing to traditional control structures (such as PI controllers), model predictive control (MPC) is able to provide fast and stable performance [2]. Regarding its high computational load, the first applications of MPC were usually related with slow dynamic systems such as chemical procedures and petroleum refineries. However, by appearance of powerful microcomputers, it is now possible to use MPC in applications with fast dynamics. In the case of electric drives, MPC is used to eliminate stator current errors in the shortest possible time [3]. Motion control applications of MPC are generally divided into three categories.

In the first category, future evolution of stator currents is estimated for all possible configurations of inverter legs. After that, a cost function is used to select the best switching state for the next modulation period. As inverter switching states are finite in each calculation step, this method is also termed Finite Control Set Model Predictive Control (FCS-MPC) [4-6].

In the second category, a combination of one zero vector and one active vector is used in the inverter to minimize the difference between stator current references and their real values. This method has been applied to control induction machines [7], doubly-fed induction machines [8], and synchronous-reluctance machines [9].

Finally, the last category of MPC (also known as deadbeat control), uses machine´s model to calculate the required voltages which lead to the desired reference currents during one modulation period. In this method, inverse model of the system (machine) is used to calculate appropriate inputs (voltages) which are required to achieve the desired outputs (stator currents) [10-12].

In the case of multi-phase electrical drives, high number of possible switching states results in high computational load in MPC algorithm [13-15]. To reduce the computational burden, many studies have considered a limited set of active vectors in their controlling algorithm. As an example, to control the stator currents of an asymmetrical six-phase machine, reference [16] has only considered the switching states which correspond to large voltage vectors and zero vectors. A pre-defined criterion is used in [17] to avoid consecutive commutations in all inverter legs and only one commutation per modulation period. As a result, in each modulation period only 6, 11 or 16 vectors are considered in MPC algorithm which significantly reduces the computational load of controlling unit.

Model predictive control is also considered in the case of five-phase electrical motors [18-20]. In [19], FCS-MPC is used to control a five-phase induction motor drive. Although the proposed method has improved the transient behaviour of the whole drive, but as it is shown, steady state behaviour is always better in the case of using PI controllers. FCS-MPC of five-phase inverters is also used in [21] to control a two-motor six-phase drive with common inverter leg topology.

Under faulty conditions, appropriate reference currents of a five-phase BLDC machine have oscillating dynamics both in phase- and rotating-reference frames [22]. As a result, high bandwidth controllers are required to control the stator currents under faulty conditions.

The main contribution of this paper is to implement and evaluate a Fault Tolerant Predictive Deadbeat Controller (FT-PDC) for five-phase BLDC motor drives. Open circuit fault is considered for one, two adjacent and two nonadjacent stator phases. This work is an extension of [23] by the same authors. Comparing to [23], the controlling algorithm is modified in consequent modulation sequences, and stator current observers are used to compensate the introduced delay of controller computations. In addition, two main aspects of proposed controlling method are evaluated in this paper. These two aspects are firstly, the sensitivity of proposed FT-PDC method, and secondly, its ability in rapidly following the reference current values.

The remaining sections of this paper are organized as follows: Mathematical model of a healthy five-phase BLDC machine and proposed FT-PDC method under normal conditions are brought in section II. The focus of section III is on application of suggested method under faulty conditions. Section IV is devoted to sensitivity analysis of proposed FT-PDC method by means of simulations. Experimental evaluation of proposed method including its sensitivity and its ability in rapidly eliminating stator current errors is brought in section V, and finally, the conclusions drawn from this study are presented in Section VI.

II. Five-Phase BLDC drive FT-PDC under Healthy Condition

A. Electrical Model of Five Phase BLDC Machine

Electrical model of five-phase BLDC machines is well studied in literature [23-24]. Similar to Park´s transformation concept in three phase systems, electrical parameters of a five-phase BLDC machine can be transferred into two rotating reference frames namely d_1q_1-frame (rotating at synchronous speed),

d_3q_3-frame (rotating at three-times synchronous speed), and a homopolar axis. This transformation can be summarized as:

$$F_{d_1q_1d_3q_3o} = T\, F_{abcde} \;,$$

$$T\left(\theta\right)=\frac{2}{5}\begin{bmatrix} \cos(\theta) & \cos(\theta-2\pi/5) & \cos(\theta-4\pi/5) & \cos(\theta-6\pi/5) & \cos(\theta-8\pi/5) \\ -\sin(\theta) & -\sin(\theta-2\pi/5) & -\sin(\theta-4\pi/5) & -\sin(\theta-6\pi/5) & -\sin(\theta-8\pi/5) \\ \cos 3(\theta) & \cos 3(\theta-2\pi/5) & \cos 3(\theta-4\pi/5) & \cos 3(\theta-6\pi/5) & \cos 3(\theta-8\pi/5) \\ -\sin 3(\theta) & -\sin 3(\theta-2\pi/5) & -\sin 3(\theta-2\pi/5) & -\sin 3(\theta-2\pi/5) & -\sin 3(\theta-2\pi/5) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \quad (1)$$

Equations of machine´s stator in two rotating reference frames and homopolar axis can be summarized as:

$$v_{d1} = r_s i_{d1} + L_{d1}\frac{d}{dt} i_{d1} - \omega L_{q1} i_{q1} \quad (2)$$

$$v_{q1} = r_s i_{q1} + L_{q1}\frac{d}{dt} i_{q1} + \omega(\psi_{pm1} + L_{d1} i_{d1}) \quad (3)$$

$$v_{d3} = r_s i_{d3} + L_{d3}\frac{d}{dt} i_{d3} - 3\omega L_{q3} i_{q3} \quad (4)$$

$$v_{q3} = r_s i_{q3} + L_{q3}\frac{d}{dt} i_{q3} + 3\omega(\psi_{pm3} + L_{d3} i_{d3}) \quad (5)$$

$$v_o = r_s i_o + L_o \frac{d}{dt} i_o \quad (6)$$

Where v and i represent stator voltage and current in each direction, r_s is the stator phase resistance, L_{d1}, L_{q1}, L_{d3}, L_{q3} and L_o are stator inductance values in their corresponding directions, and ω is the electrical rotational velocity. In addition, ψ_{pm1} and ψ_{pm3} are first and third components of magnetic field which is generated by rotor magnets.

In the case of having an isolated neutral point, i_o is forced to zero, and there will be no need to control this homopolar component of stator currents. As a result, developed electrical model of five-phase BLDC machine can be represented by four independent state variables of i_{d1}, i_{q1}, i_{d3}, i_{q3}. Moreover, Similar to three-phase PM motor drives, it is possible to use feed forward compensation to remove the cross-coupling terms of equations (2)-(5) and the terms which are due to induced back-EMF in q_1 and q_3 directions. Considering these compensations, the new representation of PM machine equations in rotating reference frames can be summarized as:

$$\begin{bmatrix} v_{d1} \\ v_{q1} \\ v_{d3} \\ v_{q3} \end{bmatrix} = r_s \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d3} \\ i_{q3} \end{bmatrix} + \begin{bmatrix} L_{d1} & 0 & 0 & 0 \\ 0 & L_{q1} & 0 & 0 \\ 0 & 0 & L_{d3} & 0 \\ 0 & 0 & 0 & L_{q3} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d3} \\ i_{q3} \end{bmatrix} \tag{7}$$

B. Proposed FT-PDC Method under Normal Operation

The main objective of the proposed deadbeat controlling method is to eliminate stator current errors in the smallest possible number of modulation periods. Center aligned space vector modulation (SVM) is used in many industrial drives. To reduce the introduced current measurement noise in such applications, current sampling is usually taken place exactly in the middle of zero-vector duty times. Moreover, implemented voltages of inverter are getting updated by the beginning of each modulation period. General sequence of stator current control is illustrated in Fig. 1.

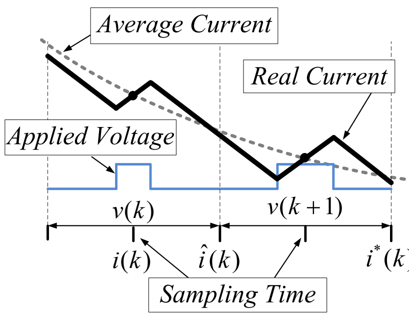


Fig. 1: General sequence of stator current drive with center aligned SVM

As it is shown in Fig.1, stator phase currents are measured in the middle of k^{th} modulation period. From this moment until the end of current modulation period, implemented reference voltages of the inverter

($V^*_{d1q1d3q3}$) will be constant. As a result, it is possible to estimate stator phase currents by the end of current modulation period:

$$\begin{bmatrix} \hat{i}_{d1}(k) \\ \hat{i}_{q1}(k) \\ \hat{i}_{d3}(k) \\ \hat{i}_{q3}(k) \end{bmatrix} = \begin{bmatrix} i_{d1}(k) \\ i_{q1}(k) \\ i_{d3}(k) \\ i_{q3}(k) \end{bmatrix} + \frac{T_m}{2}\frac{d}{dt}\begin{bmatrix} i_{d1}(k) \\ i_{q1}(k) \\ i_{d3}(k) \\ i_{q3}(k) \end{bmatrix} \qquad (8)$$

where T_m is the modulation period length. Following the main concept of deadbeat controlling algorithm, stator phase currents should be forced to reach their reference values at the end of next modulation period:

$$\begin{bmatrix} i^*_{d1}(k) \\ i^*_{q1}(k) \\ i^*_{d3}(k) \\ i^*_{q3}(k) \end{bmatrix} = \begin{bmatrix} \hat{i}_{d1}(k) \\ \hat{i}_{q1}(k) \\ \hat{i}_{d3}(k) \\ \hat{i}_{q3}(k) \end{bmatrix} + T_m\frac{d}{dt}\begin{bmatrix} \hat{i}_{d1}(k) \\ \hat{i}_{q1}(k) \\ \hat{i}_{d3}(k) \\ \hat{i}_{q3}(k) \end{bmatrix} \qquad (9)$$

By implementing (12), (13) in (11) it is possible to calculate the appropriate reference voltages for the next *(k+1)*th modulation period:

$$v^*_j(k+1) = \frac{L_j}{2T_m}(i^*_j(k) - i_j(k)) -$$

$$-\frac{1}{4}v_j(k) + \frac{r_s}{4}(i_j(k) + 2\hat{i}_j(k)) \qquad (10)$$

where j can be replaced by d_1, q_1, d_3 and q_3.

Figure 2 illustrates the general structure of five-phase PM motor drive and its controlling unit under normal (healthy) operation. By having the measured values of stator phase currents, decoupling terms of equations (6)-(9) can be calculated and added to the computed reference voltages of deadbeat controller.

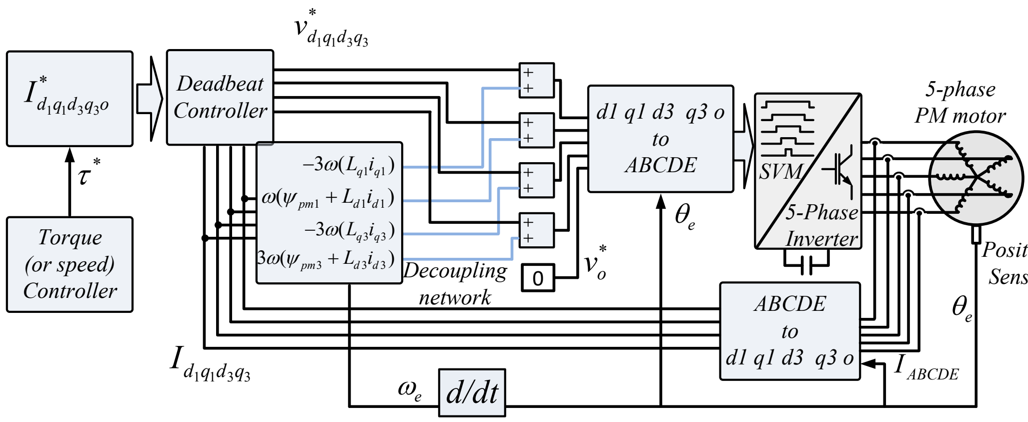


Fig. 2: Deadbeat controlling structure of five-phase BLDC motor

III. Five-Phase BLDC Drive FT-PDC under Faulty Conditions

A. Motor Model and Reference Current Adaptation for Faulty Conditions

The problem of appropriate reference currents in the case of missing one or two stator phases is studied in several papers. Table I shows the pu values of stator current references for a five-phase BLDC machine [22]. Multiplication of these current references by pu value of torque demand, results in appropriate reference currents for each modulation period.

Table I: Appropriate reference current values of five-phase BLDC machines for producing 1-pu torque under different faulty conditions [22]

Phase	A	B	C	D	E
One missing phase					
I_1	-	0,39	0,39	0,39	0,39
ϑ_1	-	45,45	134,54	-134,54	-45,45
I_3	-	0,071	0,027	0,027	0,071
ϑ_3	-	288	216	-216	-288
Two non-adjacent missing phases					
I_1	-	0,39	-	0,39	0,39
ϑ_1	-	0	-	120	-120
I_3	-	-0,07	-	0,075	0,075
ϑ_3	-	0	-	-62,8	62,8

Two adjacent missing phases					
I_1	-	-	0,23	0,39	0,23
ϑ_1	-	-	147	0	-147
I_3	-	-	0,053	0,1	0,053
ϑ_3	-	-	159	0	-159

In the case of having an open circuit fault in one of the stator phases, an additional equation should be imposed to machine´s model to consider the zero current of opened phase. Assuming phase *A* as faulty phase, this additional equation in rotating reference frames can be derived from reverse transformation of equation (5):

$$T^{-1}\begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d3} \\ i_{q3} \\ i_o \end{bmatrix} = \begin{bmatrix} 0 \\ i_b \\ i_c \\ i_d \\ i_e \end{bmatrix} \qquad ;i_a = 0 \qquad (11)$$

or

$$i_{d1}\cos(\theta) - i_{q1}\sin(\theta) +$$

$$+ i_{d3}\cos(3\theta) - i_{q3}\sin(3\theta) = 0 \qquad ;i_a = 0 \qquad (12)$$

where $\theta = \omega t$ is the electrical angle, and $\alpha = 2\pi/5$ rad.

To extract the machine´s model in the case of having one faulty phase, equation (12) should be implemented in machine´s state equations (7). Implementation of (12) reduces the number of independent state variables by one. As state variables of (7) are decoupled from each other, machine´s model in the case of missing one phase can be simply derived by ignoring one of the state variables (one raw) in (7) and directly computing it by (12).

A secondary equation should be imposed to machine´s model in the case of missing two stator phases. This additional equation while having two adjacent faulty phases (e.g. phase *A* and phase *B*) would be:

$$T^{-1}\begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d3} \\ i_{q3} \\ i_{o} \end{bmatrix} = \begin{bmatrix} i_{a} \\ 0 \\ i_{c} \\ i_{d} \\ i_{e} \end{bmatrix} \qquad ;i_b = 0 \qquad (13)$$

or

$$i_{d1}\cos(\theta-\alpha) - i_{q1}\sin(\theta-\alpha) +$$

$$+ i_{d3}\cos 3(\theta-\alpha) - i_{q3}\sin 3(\theta-\alpha) = 0 \qquad ;i_b = 0 \qquad (14)$$

Following the same procedure, the secondary imposed equation in the case of missing a non-adjacent stator phase (e.g. phase *A* and phase *C*) can be calculated as:

$$T^{-1}\begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d3} \\ i_{q3} \\ i_{o} \end{bmatrix} = \begin{bmatrix} i_{a} \\ i_{b} \\ 0 \\ i_{d} \\ i_{e} \end{bmatrix} \qquad ;i_c = 0 \qquad (15)$$

or

$$i_{d1}\cos(\theta-2\alpha) - i_{q1}\sin(\theta-2\alpha) +$$

$$+ i_{d3}\cos 3(\theta-2\alpha) - i_{q3}\sin 3(\theta-2\alpha) = 0 \qquad ;i_c = 0 \qquad (16)$$

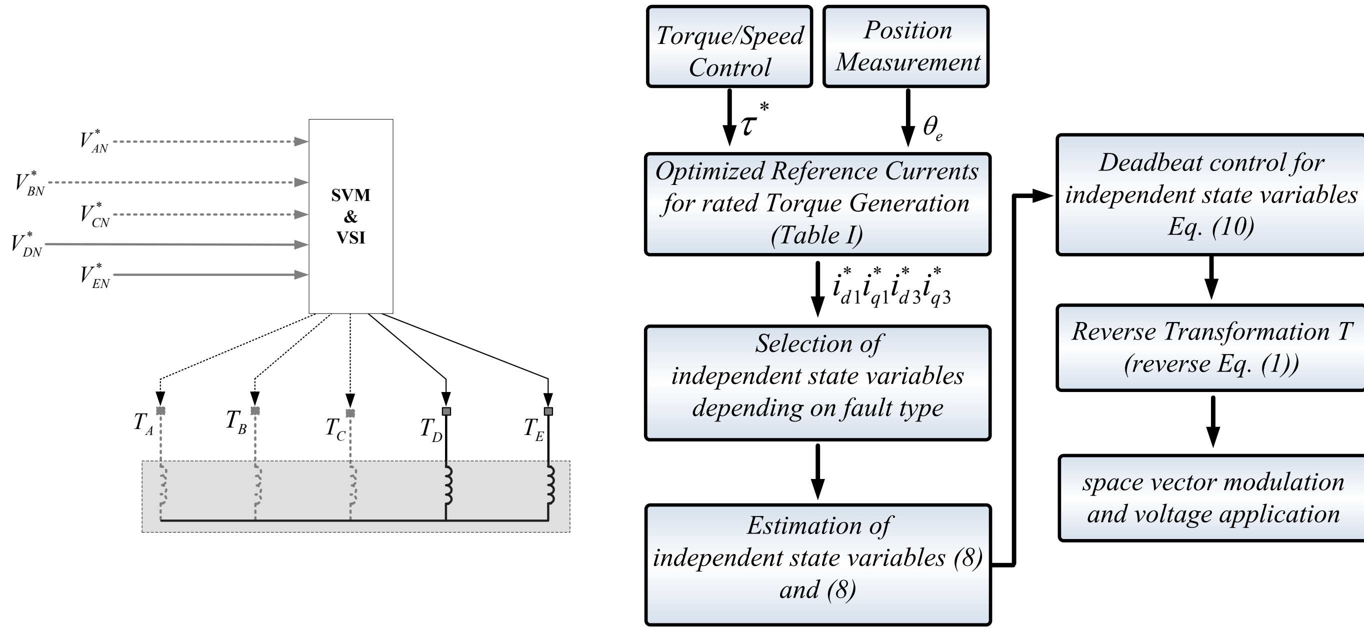
Depending on the fault type, the model of five-phase BLDC machine under faulty conditions can be directly derived by removing one or two independent state variables from (7), and calculating the removed state variables by (12), (14) or (16).

B. Proposed FT-PDC Method under Faulty Conditions

Under faulty conditions, the main objective is to control the stator currents in the remaining independent directions. Similar to the case of normal operation, in the first step independent state variables of machine´s model are estimated for the end of current modulation period. By knowing the estimated values of independent state variables, their appropriate reference voltages for the next modulation period can be computed by equation (10). To reduce the computational load, inverter reference voltages is set to zero for dependent directions.

It is important to mention that under faulty conditions, stator currents of five-phase BLDC machine are not balanced, and the voltage of machine´s neutral point is not equal to the voltage of inverter´s dc-bus midpoint. Under these conditions, the important point is to generate appropriate voltage differences between the remaining terminals of the machine. That is {V_{BC}*, V_{CD}*, V_{DE}*}, {V_{CD}*, V_{DE}*} and {V_{BD}*, V_{DE}*} respectively in the case of missing one phase (phase A), two adjacent phases (phases A and B), and two non-adjacent phases (phases A and C).

As shown in Fig. 3-(a) calculated phase-to-neutral reference voltages are computed by controller block, and will be generated by their corresponding inverter legs. These generated phase-to-neutral voltages will be imposed to the remaining phases of electrical motor. As motor terminals of missing phases are isolated, their phase-to-neutral voltages are equal to the induced back-EMF in these phases. Figure 3-(b) is a summary of deadbeat control algorithm and voltage application method under faulty conditions.



(a) (b)

Fig. 3: (a) Voltage application scheme under faulty conditions, dashed lines are correspondent to phases which can be disconnected, (b) deadbeat control algorithm of five-phase BLDC machine under faulty conditions

IV. Sensitivity Analysis of Proposed FT-PDC Method by Simulations

Simulations are conducted in MATLAB environment to evaluate the sensitivity of developed FT-PDC algorithm. Simulation parameters are summarized in table II which are also correspondent to their real values in experimental test bench.

Table II: Electrical (measured) parameters of five-phase BLDC machine

Number of Pole Pairs		26
Stator Resistance		0.1 Ω
Stator Inductance	L_{aa}	1500 *uH*
	L_{ab}	35 *uH*
	L_{ac}	42 *uH*
Nominal Torque		32 *Nm*

Nominal Phase Current	19 Amp (rms)
DC-bus Rated Voltage	48 V
Nominal current frequency	43.3 Hz
Permanent Magnet Flux	0.0178 *Wb*

In each case, the parameters of controlling block are remained constant, and at the same time, the characteristics of other simulation blocks (motor or inverter) are changed. During each test, stator current errors are evaluated in one period of fundamental frequency.

A. Simulation Steps of Sensitivity Analysis for Proposed FT-PDC Method

Simulations are completed in 6 steps. In each step a special type of disturbance is imposed to the control structure. Table III is a summary of considered disturbances during sensitivity analysis of proposed FT-PDC method.

Table III: Considered disturbances during sensitivity analysis of proposed controlling method

Test	Considered Disturbance
Test 1	None (ideal case)
Test 2	Nonlinear Inverter Characteristics
Test 3	Inaccurate Stator Resistance
Test 4 & 5	Inaccurate Magnetic Flux
Test 6	Inaccurate dc-bus Voltage

In the first step (test 1), inverter block is considered ideal, and machine parameters are equal to their corresponding values in the controlling block.

During the next step (test 2), inverter block is simulated while considering 3*us* of dead-time and real parameters of IGBTs (voltage drop and forward resistance) which are used in the experimental test.

The next simulation step (test 3) is conducted to evaluate the impact of inaccurate stator resistance on the controlling system behaviour. In this test, inverter block is ideal, and rated values of PM machine are used in computations of controlling block. In addition, stator resistances are doubled in machine´s model.

The effect of flux amplitude variation is evaluated in the next two simulation steps. Again, inverter block is considered ideal, and controlling unit parameters are considered equal to motor rated values. At the same time and in the motor block, rotor magnetic flux is lowered down to 0.8 its rated value (test 4), and in the next step (test 5) it is increased up to 1.2 its rated value.

The effect of dc-bus voltage drop is evaluated in test 6. Nominal voltage of inverter dc-bus is used in controlling block computations. At the same time, dc-bus voltage is set to 0.8 rated value in inverter block.

B. Simulation Results and Discussion

In each test, the energy of phase current errors is computed and integrated over one period of fundamental current frequency in (17):

$$E_{error} = \int_T (\Delta i_{d1}^2 + \Delta i_{q1}^2 + \Delta i_{d3}^2 + \Delta i_{q3}^2) dt \qquad (17)$$

Figure 4 shows the pu values of error energy for different tests and under each operational condition.

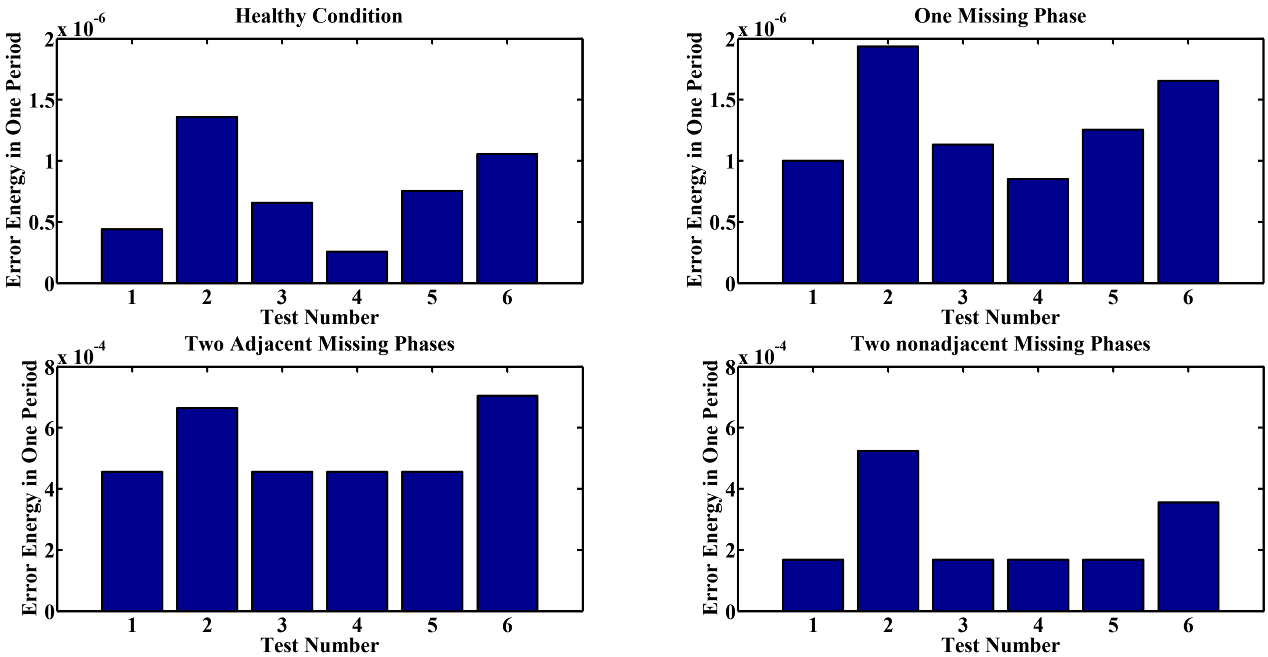


Fig. 4: pu energy values of phase current error in one period of fundamental frequency

As it is shown in Fig. 4, under normal conditions the pu values of error energy in one period of fundamental frequency are less than 1.5 [uA^2 pu]. The main reason of current error in ideal simulations (test 1) can be referred to nonlinear behaviour of PM machine which introduces error in "current estimation step" and "voltage computation step". During "current estimation step", the derivative of stator currents in each direction will be calculated by using the measured values of currents in the middle of modulation step:

$$\frac{d}{dt}i_j = \frac{1}{L_j}(v_j - r_s i_j) \tag{18}$$

where *j* can be d_1, q_1, d_3 *and* q_3, and i_j represents the sampled value of stator currents in each direction. Calculated values of current derivatives are assumed to be constant until the end of current modulation period. In addition, during "voltage calculation step" of control algorithm, the derivative of estimated currents is considered as a fixed value during the next modulation period. Variation of stator currents introduces error in both "estimation step" and "voltage computation step" of control algorithm.

As it can be seen from Fig. 4, nonlinear characteristics of the inverter (test 2) and dc-bus voltage errors (test 6) are correspondent to the highest values of stator current errors. In fact, nonlinear characteristics of the inverter (including deadbeat implementation and voltage drops along the IGBTs and diodes) can also be considered as a voltage drop of machine´s power supply unit.

To have an analytical evaluation on how dc-bus voltage drop can increase the stator current errors, let us assume that there is a difference between assumed values of applied voltage (in controlling unit) and their real values:

$$v_j(k) = v_{real}(k) + \Delta v_j(k) \tag{19}$$

where $v_j(k)$ and $v_{real}(k)$ are respectively the assumed and real values of applied voltage in direction *j*. The existing error in the assumed value of applied voltage ($\Delta v_j(k)$) results in an additional error in the estimated value of stator currents by the end of current modulation period:

$$i_{es} = i_k + \frac{T_m}{2}\frac{1}{L_j}(v_{real}(k) + \Delta v(k) - r_s i_k)$$

$$= \left[i_k + \frac{T_m}{2}\frac{1}{L_j}(v_{real}(k) - r_s i_k) \right] + \left[\frac{T_m}{2}\frac{1}{L_j}\Delta v(k) \right]$$

$$= i_{es(normal)} + \Delta i_{es} \tag{20}$$

where $i_{es(normal)}$ is the estimated value of stator current in direction *j* under normal conditions, and Δi_{es} is the additional term which is generated due to dc-bus voltage error. In the next step, estimated value of stator current i_{es} will be used to calculate the appropriate reference voltage during the next modulation period:

$$v^*(k+1) = (i^* - (i_{es(norm)} + \Delta i_{es}))\frac{L}{T_m} + r(i_{es(norm)} + \Delta i_{es})$$

$$v^*(k+1) = \left[(i^* - i_{es(norm)})\frac{L}{T_m} + r(i_{es(norm)}) \right] + \left[\frac{\Delta v(k)}{2}(\frac{r_s}{L}T_m - 1) \right]$$

$$= v^*(k+1)_{(norm)} + \Delta v^*(k+1) \tag{21}$$

where $v^*(k+1)_{norm}$ is the calculated reference voltage under normal conditions, and $\Delta v^*(k+1)$ will be imposed to direction *j* due to dc-bus voltage error. Considering simulation parameters of table II and a switching frequency between 5-20 kHz, it can be concluded that:

$$\Delta v^*(k+1) \approx -\frac{\Delta v(k)}{2} \tag{22}$$

In other words, in the case of having $k\%$ of error in dc-bus voltage, applied voltage amplitudes in $d_1q_1d_3q_3$-directions will be multiplied by $(100 - \frac{k}{2})\%$ which results in higher amplitude of error energy.

In the case of missing one stator phase, the same pattern of error energy can be observed from Fig. 4. However, comparing to healthy mode operations, the energy of phase current errors is relatively higher.

One of the reasons of higher error energy in the case of missing one-phase is higher dynamics of current reference values under faulty conditions. Figure 5 illustrates the derivative of stator currents in $d_1q_1d_3q_3$-directions under faulty conditions. As it was explained, while FT-PDC algorithm is being executed, stator current derivatives are assumed to be fixed in "current estimation" and "voltage computation" steps, and variation of current derivatives will increase the energy of stator current errors.

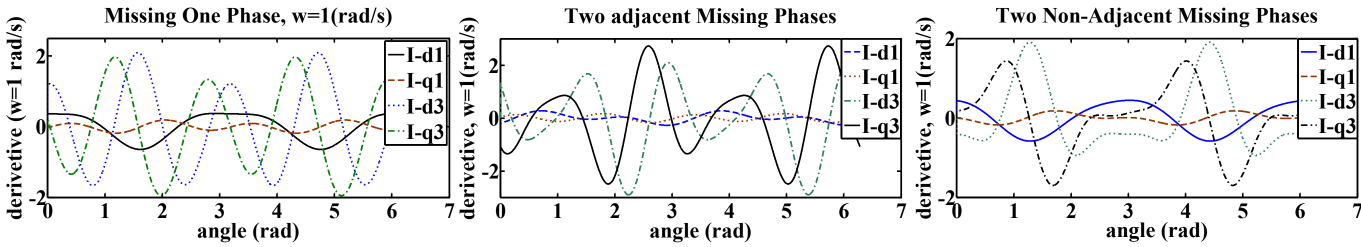


Fig. 5: Derivative of reference currents in the case of missing one stator phase (e. g. phase A), two adjacent faulty phases (e. g. phase A and B), and two non-adjacent faulty phases (e. g. phase A and C)

Following the same pattern, the energy of stator current error increases in the case of missing two stator phases. Again nonlinear inverter characteristics (test 2) and lower amplitude of dc-bus voltage (test 6) are correspondent to the highest amplitude of current errors. While missing two phases, stator currents should be estimated in two (independent) directions. To compute the stator currents in the remaining directions, estimated values of independent state variables should be used in (23) or (24) to calculate the stator currents of the remaining (dependent) directions:

$$\begin{cases} i_{d1}\cos(\theta) - i_{q1}\sin(\theta) + i_{d3}\cos(3\theta) - i_{q3}\sin(3\theta) = 0 \\ i_{d1}\cos(\theta-\alpha) - i_{q1}\sin(\theta-\alpha) + i_{d3}\cos 3(\theta-\alpha) - i_{q3}\sin 3(\theta-\alpha) = 0 \end{cases}$$; two adjacent faulty phases (23)

$$\begin{cases} i_{d1}\cos(\theta) - i_{q1}\sin(\theta) + i_{d3}\cos(3\theta) - i_{q3}\sin(3\theta) = 0 \\ i_{d1}\cos(\theta-2\alpha) - i_{q1}\sin(\theta-2\alpha) + i_{d3}\cos 3(\theta-2\alpha) - i_{q3}\sin 3(\theta-2\alpha) = 0 \end{cases}$$; two non-adjacent faulty phases (24)

Again, dynamic behaviour of phase current derivatives in different directions leads to current error in both estimation and computation steps of the controlling algorithm.

V. Experimental Evaluation of Proposed FT-PDC Method

A. Test Bench Explanation

Experimental tests are completed to evaluate the behaviour of proposed FT-PDC method in five-phase PM motor drives. General configuration of laboratory test bench is illustrated in Fig. 6.

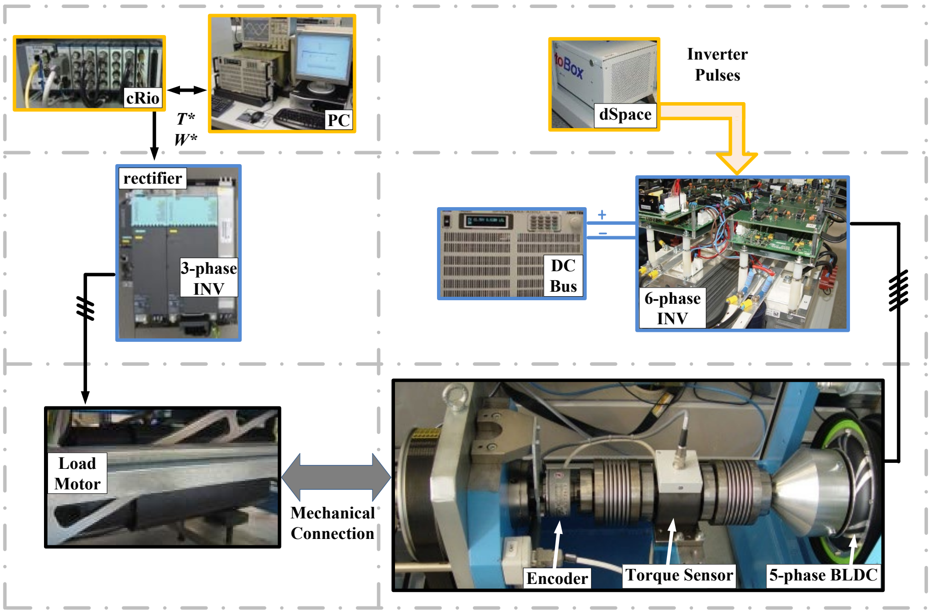


Fig. 6: Test bench configuration

The implemented five-phase BLDC machine is including a double-layer fractional-slot winding configuration. Regarding its outer rotor structure and high power density, it is possible to directly mount the motor inside the vehicle´s wheel. Measured back-EMF waveform of stator winding phase includes 11% of 3rd harmonic component and 5% of 7th harmonic component.

In each experiment, stator terminals of the remaining healthy phases are directly connected to inverter outputs, faulty phases will be disconnected from the inverter.

A DS1005 dSpace board is used to 1) execute the proposed predictive deadbeat control, 2) realize five-phase center-aligned SVM, and 3) generate the required controlling pulses for the inverter. Due to limited computational power of the dSpace, the switching frequency is fixed on 5 kHz. Hall Effect sensors are used to establish stator current feedbacks, and position feedback loop is realized by means of a 9000-pulse/revolution incremental encoder.

The main focus of the paper is on stator phase current controllers. As a result, evaluated controlling algorithms are correspondent to torque control of five-phase BLDC machine. Rotational velocity is fixed on its rated value by the load system which is a commercial three-phase motor drive known as SINAMICS-S120. The required interference between the host PC and SINAMICS-S120 is established by a real-time controller made by National Instruments (known as cRio).

B. Measured Values of Torque and Stator Currents

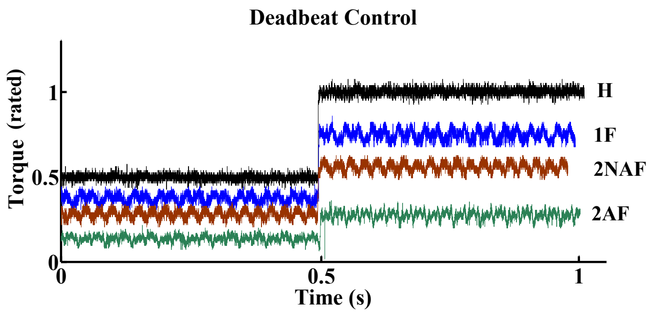
Measured values of stator phase currents and mechanical torque are shown in Fig. 7 for different operational conditions.

In each case reference torque is changed from 0.5 to 1.0 of its maximum achievable value. A four-channel digital oscilloscope is used to simultaneously record the generated torque and phase currents in three stator phases. As a result, under normal condition only three stator phases (phases B, C and D) are shown. Due to machine´s isolated neutral point, total sum of stator phase currents is always zero. Therefore, in the case of having one faulty phase, stator current of phase B, C and D are directly measured and stator current of phase E is calculated.

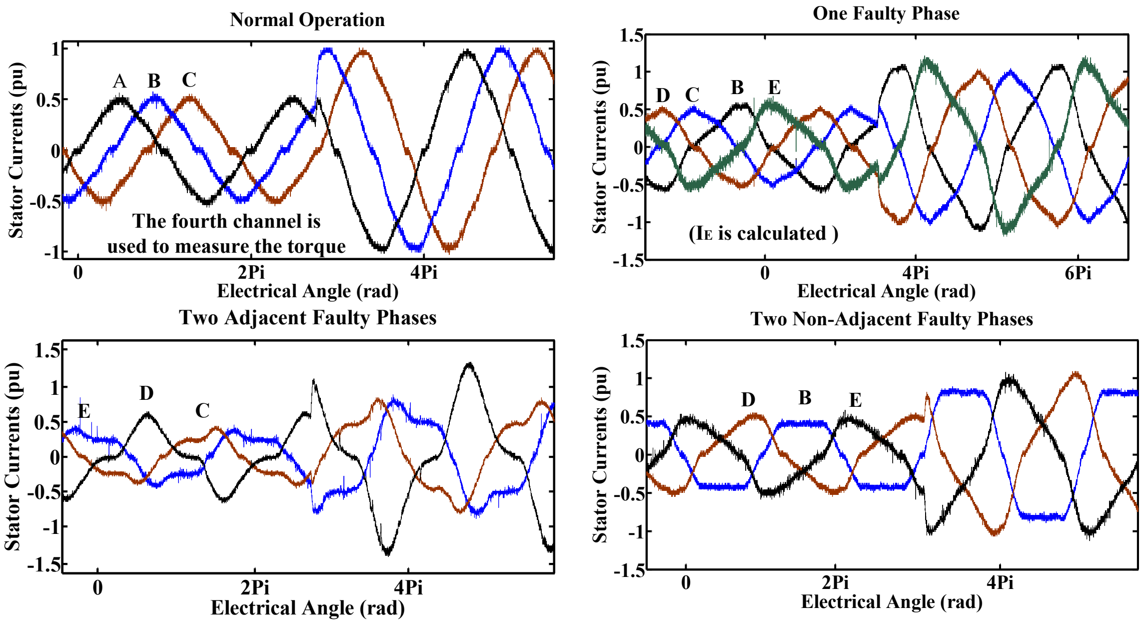
One of the typical sources of current error in predictive deadbeat control algorithms is unmeasured disturbances and parameter variations. As controller outputs are only dependent on the current values of system states (and not system past history), both system parameter variations and disturbance injection can lead to non-zero values of steady-state torque error. This problem is resolved in this study by adding an integrator in the controlling loop of generated torque. That is to consider all disturbances as one additional signal on machine´s generated torque, and estimating this signal by integrating the difference of generated torque (τ_{real}) and its reference value. In other words, instead of using reference torque (τ_{ref}), the following value ($\overline{\tau}_{ref}$) is used to compute stator current references:

$$\overline{\tau}_{ref} = \tau_{ref} + K_{\text{int}} \int (\tau_{ref} - \tau_{real}) \ dt \tag{25}$$

where K_{int} should be adjusted to eliminate the steady state error of generated torque. In this study, this value is set to 5 which lets us to eliminate the steady state error without noticeable influence on machine´s dynamic behaviour.



(a)



(b)

Fig. 7: (a) Measured values of generated torque under healthy (H) condition and while missing one phase (1F), two adjacent phases (2AF), and two non-adjacent phases (2NAF), (b) Stator phase currents under healthy and different faulty conditions (In each case, generated torque is measured by one channel, and three stator phases are measured by the remaining channels of oscilloscope)

C. Dynamic Analysis of Proposed FT-PDC Method - Transient States

To evaluate the dynamic behaviour of proposed FT-PDC method, under each operational condition reference value of torque is changed from 0.5 to 1.0 its maximum achievable value.

Measured value of electrical torque rise-time during transient states is 0.6 ms which is equal to 3 consecutive modulation periods. However, the theoretical value of rise-time should be equal to one modulation period (0.2 ms). The main reason of longer rise-time period is the limited value of inverter dc-link voltage. In other words, the required voltage for removing the stator current errors during only one modulation period is higher than available dc-link voltage which extends the rise-time to three consecutive modulation periods.

To have an analytical evaluation on the measured torque values, the energy of torque error is computed during transient states. Switching frequency is set on 5 kHz, and the sampling rate of oscilloscope is set on 50 kHz. 4000 samples (equal to 400 modulation periods) are measured while the transient state is placed in the middle of sampling period. The energy of torque error is integrated for all of these samples:

$$E = \sum_{4000} (T_{measured} - T_{reference})^2 \tag{26}$$

This error is also evaluated for the case of operating under steady states. Calculated values of torque error energy are summarized in Table IV.

Table IV: Calculated values of torque error energy under different operational conditions

Error Energy-pu [Nm^2]	H	1F	2AF	2NAF
Transient				
deadbeat control	2.83	3.39	4.01	3.83
Steady state				
deadbeat control	0.87	2.36	3.29	2.67

Comparing to steady state operations, in each case the energy of torque error is higher in transient state operation which is due to high value of reference current changes under transient operations. Moreover, in each raw of table IV, the energy of torque error rises by increasing the number of faulty phases. This fact is in accordance with the increasing rate of current errors while missing more stator phases. In addition, comparing to the case of missing two adjacent stator phases, missing two non-adjacent stator phases results in less torque (and current) error which is due to more symmetric position of the remaining stator phase windings and less dynamics of stator reference currents in this case.

D. Sensitivity Analysis of Proposed FT-PDC Method - Steady State Conditions

To verify the simulation results, three different experiments are conducted in laboratory to evaluate the sensitivity of proposed FT-PDC method. However, there are some limitations in experimental evaluation of sensitivity for proposed controlling method. The first limitation is related to inverter nonlinear characteristics. As electrical motor is always fed by a five-phase inverter it is not possible to experimentally evaluate the ideal case which was considered in simulations (ideal inverter with no dead time and no voltage drop in semiconductors). In addition, rotor magnets (and their corresponding magnetic flux) are constant during all experimental tests. A summary of conducted experiments is brought in Table V.

Table V: Conducted experiments to evaluate the sensitivity of proposed controlling method

experiment	Real situation	Controlling unit assumption
experiment-1	nonlinear inverter characteristics	Ideal inverter
experiment-2	nonlinear inverter characteristics and doubled value of stator resistance	Ideal inverter, and rated value of stator resistance
experiment-3	nonlinear inverter characteristics and dc-link reduction in the inverter	Ideal inverter and rated value of dc-link in inverter

During the first experimental evaluation (experiment-1), precise values of machine parameters are used in calculations of controlling unit. In the next step (experiment-2), stator resistances are doubled by adding additional resistances in series with stator phase terminals. But their correspondent value in controlling algorithm is not changed. For the next evaluations (experiment-3), dc-link voltage of the inverter is reduced to 0.8 its rated value while in controlling unit, rated value of dc-link voltage is used for reference voltage calculations. Under each operational condition, the energy of stator current errors is integrated over one period of fundamental frequency under steady-state operation, and brought in Fig. 8 for more comparisons.

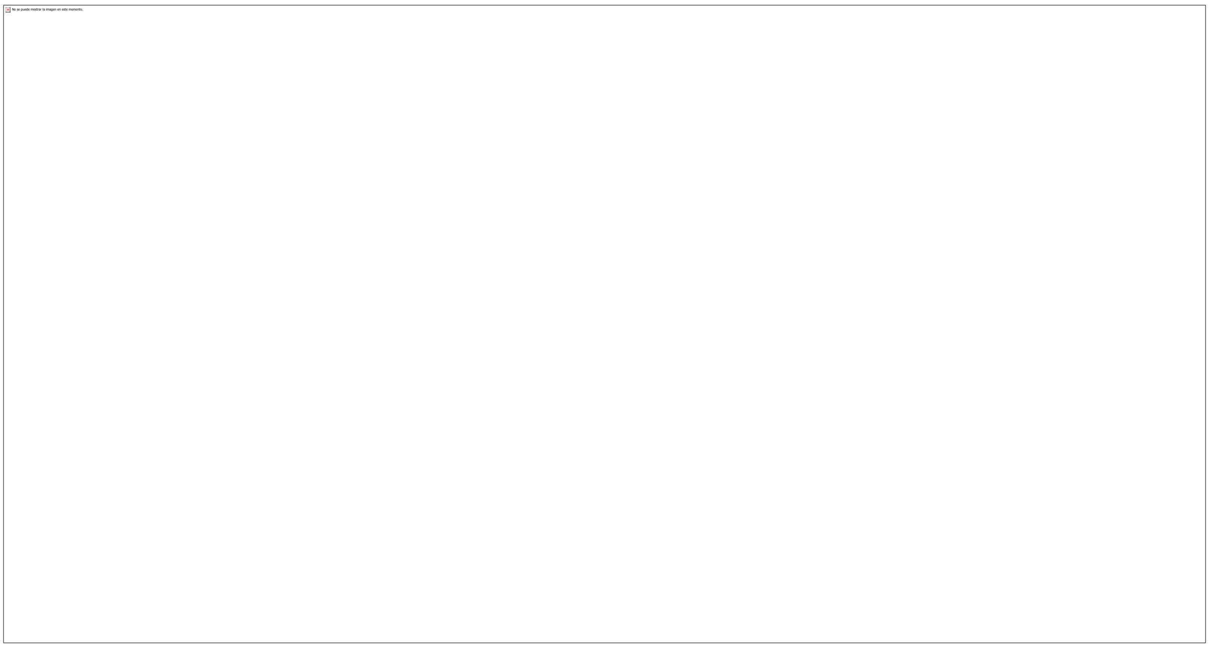


Fig. 8: pu energy values of phase current error in one period of fundamental frequency

Measured values of current error energy are in accordance with simulation results under all operational conditions. In these cases, the minimum value of measured error is related to experiment-1 which only includes the nonlinear characteristics of the inverter. In addition, under each operational condition, the energy of error in “experiment-1” is higher than 50% of its value in “experiment-2” and “experiment-3”. By considering table V, it is possible to write:

(27)

and

(28)

where $E_{nonlinear\ INV}$, E_{Rs}, and $E_{dc\text{-}link}$ are respectively the energy of stator current errors due to “nonlinear inverter characteristics”, “stator resistance increment”, and “inaccurate dc-link voltage”. This result is in accordance with simulation results where under all conditions, the highest value of stator current errors were because of nonlinear inverter characteristics.

Moreover, as it can be seen from Fig. 8, under all operational conditions the energy of current errors in “experiment-3” is higher than its value in “experiment-2”:

(29)

which means that in each case introduced error due to wrong dc-link value is higher than introduced error due to wrong stator resistance error. This result is also in accordance with simulation results in Fig. 4. Similar to simulation results, the error of currents increases by increasing the number of faulty phases which is due to higher variations (dynamics) of stator reference currents under faulty conditions.

VI. Conclusion

In this study, model predictive deadbeat control is developed for the case of five-phase BLDC motor drives under healthy and faulty conditions. Open circuit fault is considered in the case of missing one, two adjacent, and two nonadjacent stator phases. Proposed controlling method is designed to estimate the stator currents for the end of current modulation period, and eliminate the stator current errors during the next modulation period. Limited values of dc-link voltage can lead to slower dynamics of proposed method during transient states. Sensitivity of proposed controlling method is evaluated, and it is shown that nonlinear characteristics of inverter switches and inaccurate dc-bus voltage have the most noticeable impact on the error of stator phase currents. Therefore, these two parameters should be taken into account in practical predictive control applications of five-phase BLDC drives. Both simulations and experimental evaluations show that the proposed method is robust and able to provide fast current response with no overshoot under healthy and open-circuit faulty conditions of five-phase BLDC machines.

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